STUDIES FOR STUDENTS.

DEFORMATION OF ROCKS.—II. AN ANALYSIS OF FOLDS.

CONTENTS.

As ordinarily treated, folds are considered as simple flexures in two dimensions. As they occur in nature, folds are complex flexures in three dimensions.

Folds in rocks may be compared with the waves of the sea. Each large wave has superimposed upon it waves of the second

order; upon these are waves of the third order, and on these waves of the fourth order, and so on. Moreover, running across the most conspicuous waves at various angles up to perpendicularity may be other waves of an equally composite character. As observed from a ship at sea the waves of the first order are so large and have such gentle slopes that they are often overlooked, while the steeper waves of the second order are noticed, because more conspicuous. On account of their small size the waves of a higher order than the second are usually unnoticed, as are also the waves of all orders which are transverse to the more conspicuous set.

If when stirred by a great storm the surface of the sea could in an instant be frozen, we should obtain some idea of the complexity of the waves. We should see primary elevations and depressions of circular, oval, and lenticular horizontal sections, in different sets, crossing one another in various directions, and upon these would be other sets of waves of like complexity of the second, third, and fourth orders, and so on.

The rock waves of the earth are of greater size and of equal or greater complexity than the waves of the sea. The rollers of the sea, when not wind forced may be compared with the long, gentle folds of rock. At first sight they seem simple, but, like the rock folds, when observed closely they are found to possess secondary crenulations. At the other extreme are the highly complex waves running in various directions at the same time, formed by the shifting winds of a great storm, by currents and tides together. The sea in this condition may be compared with the rocks in which each set of primary folds has superimposed upon them folds of the second order, and upon these those of a higher order to the *n*th order. The smaller orders of folds are microscopic. Such complex rock folds are called crumpled, plicated, or implicated.

In this comparison it is not meant to imply that the forces which produce rock folds are the same, or that they work in the same manner, as the forces which produce sea waves. Nor is it meant that the forms of the folds are the same as the forms of

the waves. The only purpose of the comparison is to give at the outset some idea of the complexity of rock folds.

Tangential thrust and gravity are assumed to be the causes of folds. No attempt will be made here to show this or to explain the cause of thrust, although in the last analysis it is probable that thrust is dependent upon gravity. At all times and in all positions rocks are subject to the force of gravity. Thrust and gravity act upon rocks of heterogeneous character. Rock heterogeneity, therefore, modifies the forms of folds. Folds are further modified by igneous rocks. In what follows, the effects of igneous rocks are at first excluded.

We shall now attempt to analyze the rock waves or folds. For convenience, they will first be considered in two dimensions.

SIMPLE FOLDS.

Simple folds are classified by de Margerie and Heim[1] as follows: A fold is upright or symmetrical when the axial plane is vertical, or nearly so, and the limbs have nearly equal dips in opposite directions at corresponding points (Fig. 1).

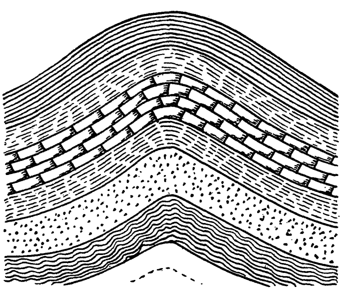

FIG. 1.—Simple upright fold.

A fold is inclined or symmetrical when the axial plane is inclined and the limbs have unequal dips in opposite directions at corresponding points (Fig. 2).

A fold is overturned or overfolded when the axial plane is inclined and the limbs have equal or unequal dips in the same direction at corresponding points (Fig. 3). An overturned fold is lying or recumbent when its axial plane is horizontal, or nearly so (Fig. 4). The different parts of an overturned fold are the arch limb, reversed limb, and trough limb (*a*, *b*, *c*, Fig. 4).

As to closeness of compression, folds are described by de

[1] Les dislocations de l'écorce terrestre, par EMM. DE MARGERIE et ALBERT HEIM, Zürich, 1888, pp. 49–63.

Margerie and Heim as follows: An ordinary fold is one in which the strata diverge from the crest of the anticline and the trough of the syncline (Figs. 2–4). Ordinary folds may be described as

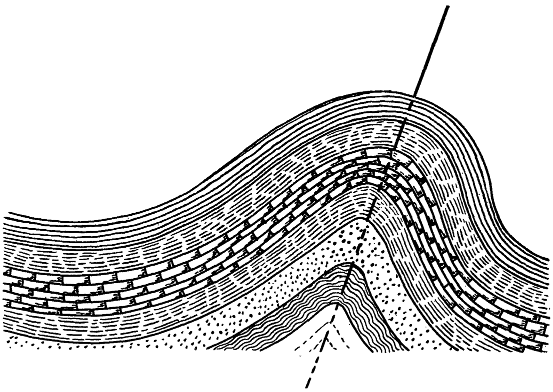

FIG. 2.—Simple inclined fold.

gentle, open, or close. In close folds, according to Willis, the process has gone so far that the strata are perceptibly changed in thickness in different parts of the fold. An isoclinal fold

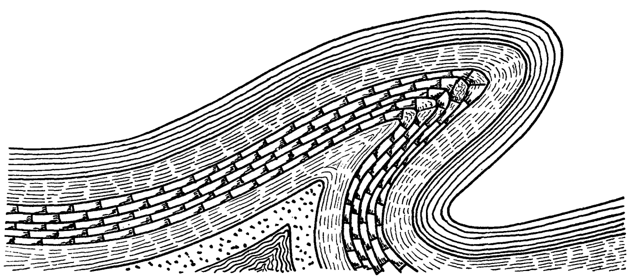

FIG. 3.—Simple overturned fold.

is one in which the strata are parallel, or nearly so (Fig. 5). A fan fold is one in which the strata converge downward from the crest of the anticline (Fig. 9), or upward from the trough of the syncline. In this case the strata at the limbs of the fold are always greatly thinned, and in some instances the central strata are absent, the material having flowed up and down, form-

ing detached arch cores and detached trough cores. An ordinary, isoclinal, or fan fold may be upright, inclined, or overturned.

In the formation of the simple fan-shaped anticline the

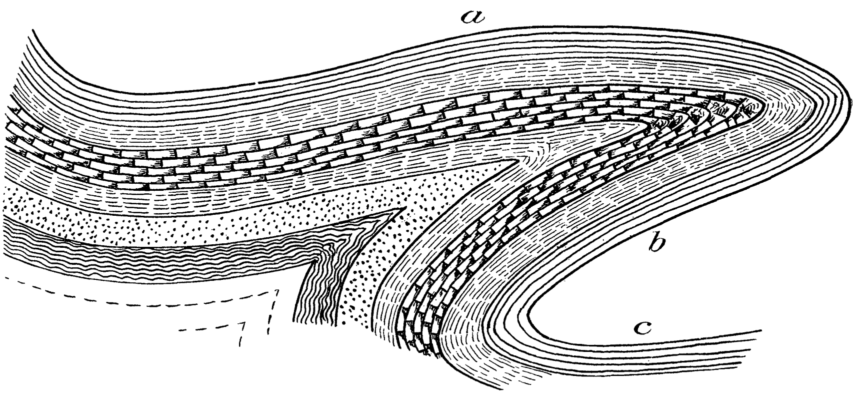

FIG. 4.—Simple recumbent fold.

rocks are extremely compressed on the limbs of the fold, while on the anticline the compression is not so severe. This is doubtless due to the partial escape from pressure of the material which

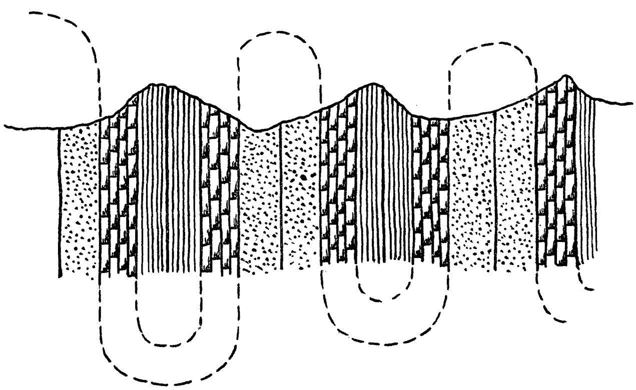

FIG. 5.—Simple isoclinal folds.

rises into an arch, as compared with the deeper-seated material in the limbs of the folds, which constitutes a part of the continuous crust of the earth in which the major thrust must have been transmitted. Another factor is the relative strength

of the layers. A strong stratum may deform weaker layers, geologically below, into the fan form by producing flowage in them. The formation of the fan fold may be further assisted

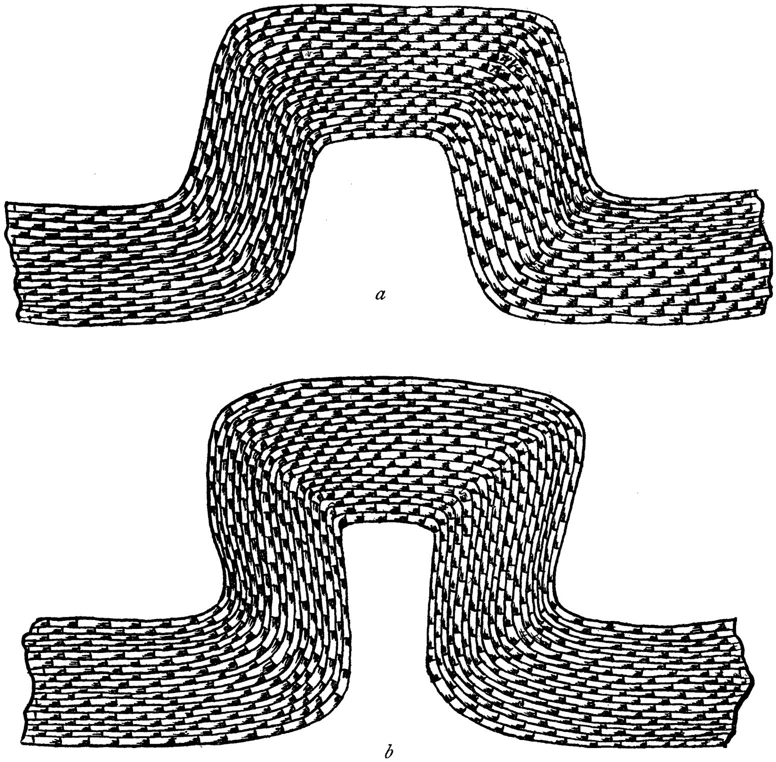

FIG. 6.—*a*, Diagram of fold in limestone of the Jura Mountains, showing hinge-like bending at sides of anticlines: *b*, the same somewhat more closely compressed, so that the fold has become fan-shaped.

by the tendency of rocks to bend farther at a place where deformed rather than to bend in a new place. The different phases of the formation of fan folds are illustrated in the Jura. In the folds of certain parts of the Jura one is impressed with the flatness of the anticlinal domes and the synclinal troughs, the steepness of the limbs, and the rapidity of the change from flat dips at the anticlines and synclines to nearly vertical dips on the

limbs of the folds (Fig. 6*a*). So quick is the change that the folds may be said to have corners, where the beds are bent in a circular fashion almost within their own radius. In the more closely compressed folds the beds constituting opposite limbs of the folds are overturned in opposite directions, thus producing a true fan fold (Fig. 6*b*). It is clear that the material of the domes partly escaped the thrusts which were transmitted in the solid rocks below. This thrust from both directions pressed the lower parts of the limbs closer and closer together, while the rigidity of the partly free dome above prevented the upper part of the legs from following, and thus the limbs were overturned in opposite directions. It is probable that the folds in the Jura represented by Fig. 6 were not very deeply buried, and that had the material been much deeper the more regular form of fan fold shown by Fig. 9, and characteristic of the Alps, would have been produced. It may be suggested that the Jura and the Alps belong to the same great geological province, and since the types of folding are the same in both mountain ranges it is not improbable that if the Jura were uplifted sufficiently and more deeply denuded the ordinary fan-shaped fold of the Alps would be revealed.

It follows from the above that the mechanics of the formation of fan-shaped synclines are not the same in all respects as those of the anticlines. It can hardly be assumed that synclines are of such magnitude that the lower parts reach a level in which the thrusts are less than at a higher level. In other words, it cannot be assumed that the lower part of the trough of a syncline is under less lateral compression than the center of the fold. This may, however, be the case if a "level of no strain" is so near the surface as two miles. Even if this supposed level is not at a greater depth than seven or eight miles, Davison's later estimate, the thrust may be considerably less at the deeper parts of the fold than at the places of greatest lateral force. We therefore do not know whether the first and probably the most important cause of the production of fan-shaped anticlines—difference in amount of thrust—may also apply to the produc-

tion of fan-shaped synclines. A difference in the strength of layers and a tendency for layers to continue to bend at certain places when bending has begun, rather than at other places, may tend to produce fan-shaped synclines. For instance, if a very strong layer is between two weaker layers, and this stronger layer becomes bent more decidedly at the outer, upper parts of the syncline, it may continue to bend at these places, and by its strength deform the softer material above and below it, so as to force the whole into a fan form. That minor fan-shaped synclines are thus produced is highly probable, but it may be doubted whether fan-shaped synclines of the first order would be thus formed, although they may be produced by differential thrust if the theory of a "level of no strain" be true.

COMPOSITE FOLDS.

The greatest flexures of the earth's crust are termed by Dana *geanticlines* and *geosynclines*. Generalizing from his illustrations, it appears that these may be defined as flexures which are predominantly due to the force of gravity in its tendency to produce isostatic adjustment. The deforming force is therefore mainly vertical. When rocks are subjected to strong lateral forces they are also deformed, and mountain ranges are produced. All folds, of whatever magnitude, thus made by the work of great lateral thrust and gravity combined, when not simple, are called, following Dana, *anticlinoria* and *synclinoria*. An anticlinorium or synclinorium of the first order of magnitude is one which comprises an entire mountain range. Illustrating this usage of the terms, the great geological province or basin of deposition of which the Jura, the great valley of Switzerland, and the Alps occupy a part, was a geosyncline. When subjected to orogenic forces the mountain ranges now seen were produced. The Alps and Jura, taken as wholes are anticlinoria of the first order, and the great valley between is a synclinorium of the first order.

The various kinds of simple folds may be united to produce a great variety of composite structures. A composite fold may be an anticlinorium or a synclinorium. An anticlinorium or

synclinorium, like a simple fold, may be upright, inclined, or overturned, but it is probable that in composite folds of the first order of magnitude the last rarely if ever occurs.

Taking as axial planes the radial planes of the primary fold, the secondary folds may be upright, inclined, or overturned, or on different parts of the same primary fold each form may occur. The radial positions of the axial planes give the proper basis in comparing the dynamic processes and effects of folding, but

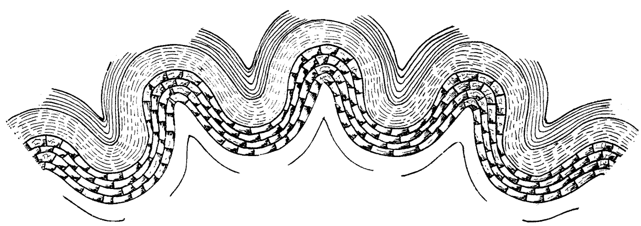

FIG. 7.—Ideal section of an upright normal anticlinorium.

because we rarely see the whole of a great anticlinorium or synclinorium at a single view, it is perhaps best to treat both the primary and secondary folds in reference to the plane of horizon.

Some of the special cases of composite folds are as follows:

NORMAL COMPOSITE FOLDS.

The upright normal anticlinorium.—The primary fold of the upright normal anticlinorium has a vertical or nearly vertical axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions.

(*a*) The primary fold is composed of a set of secondary folds each of which is upright or nearly so, taking the radial planes of the primary fold as axial planes of the secondary folds. Referring the axial planes to the horizon, at the crest of the anticline the secondary folds are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are inclined, but not overturned. The two sets of secondary axial planes on opposite sides of the crest of the primary fold diverge upward and converge downward (Fig. 7).

(*b*) Composed fan fold. The primary fold is composed of a set of secondary folds which at the crown are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The secondary folds may be ordinary, isoclinical, or fan-shaped. The

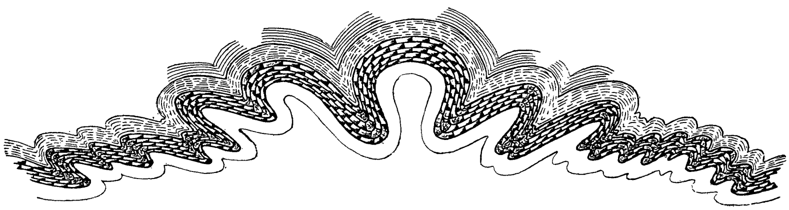

FIG. 8.—Ideal composed fan fold.

two sets of secondary axial planes on opposite sides of the crest of the primary fold diverge upward and converge downward (Figs. 8 and 9). Often in extreme cases of compression at

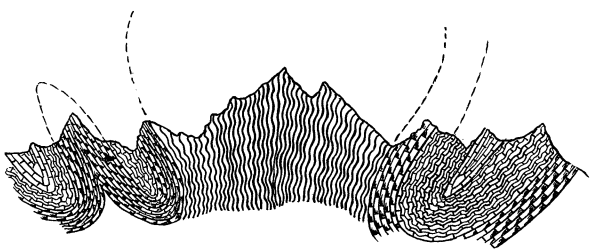

FIG. 9.—Generalized fan-fold of the central massif of the Alps. After Heim.

the crest of the primary anticline the secondary folds are fan-shaped, and passing in either direction these grade into isoclinal and then into ordinary folds. Such are many of the composite folds of the Alps.

The inclined normal anticlinorium.—The primary fold of the inclined normal anticlinorium has an inclined axial plane and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the crest of the

primary fold diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The overturned normal anticlinorium.—The primary fold of the overturned normal anticlinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same

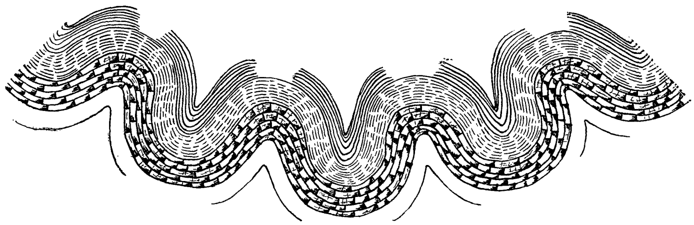

FIG. 10.—Ideal section of an upright normal synclinorium.

direction as the primary fold. The two sets of secondary axial planes on opposite sides of the crest of the major fold diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The upright normal synclinorium.—The primary fold of the upright normal synclinorium has a vertical or nearly vertical axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions.

(*a*) The primary fold is composed of a set of secondary folds, each of which is upright, or nearly so, taking the radial planes of the primary fold as axial planes of the secondary folds. Referring the axial planes to the horizon at the trough of the synclinorium, the secondary folds are upright, and in passing in either direction transverse to the primary axial planes the folds are inclined, but not overturned. The two sets of axial planes on opposite sides of the trough of the major fold converge upward and diverge downward (Fig. 10).

(*b*) Inverted intermont trough.[1] The primary fold is composed of a set of secondary folds, which at the center of the trough

[1] Les dislocations de Pécorce terrestre, par EMM. DE MARGRIE et ALBERT HEIM p. 83. Zürich, 1888.

are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial planes on opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped (Fig. 11).

The inclined normal synclinorium.—The primary fold of the

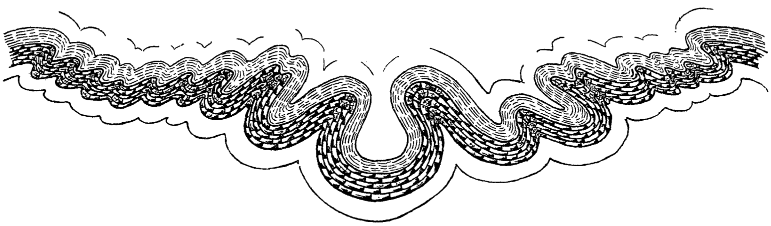

FIG. 11.—Ideal section of an inverted intermont trough.

inclined normal synclinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal or fan-shaped.

The overturned normal synclinorium.—The primary fold of the overturned normal synclinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of axial planes of the secondary folds on the opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

ABNORMAL COMPOSITE FOLDS.

The upright abnormal anticlinorium.—The primary fold of the upright normal anticlinorium has a vertical, or nearly vertical, axial plane, and the limbs at corresponding points have nearly

equal average dips in opposite directions. The primary fold is composed of a set of secondary folds, which at the crest are upright, and in passing in either direction transverse to the

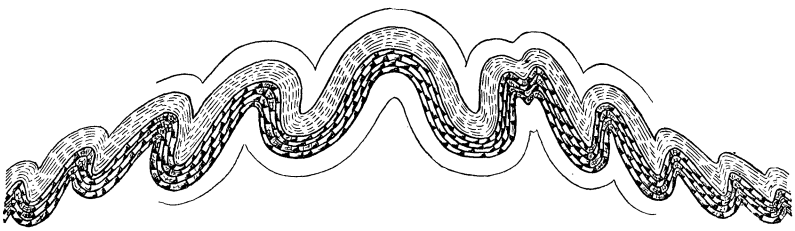

FIG. 12.—Ideal section of an upright abnormal anticlinorium.

primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial planes on opposite sides of the crest converge upward and diverge down-

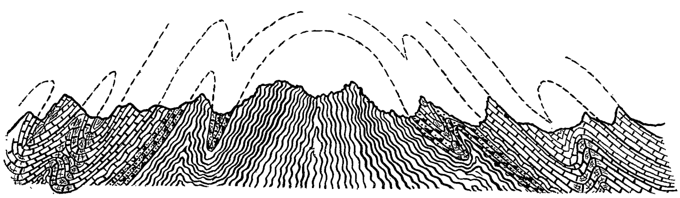

FIG. 13.—General section of roof structure in the central massif of the Alps. After Heim.

ward. The secondary folds may be ordinary, isoclinal, or fan-shaped (Figs. 12 and 13).

The inclined abnormal anticlinorium.—The primary fold of the inclined abnormal anticlinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, all of which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the crest converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The overturned abnormal anticlinorium.—The primary fold of the overturned abnormal anticlinorium has an inclined axial plane,

and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of secondary axial planes on opposite sides of the crest converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

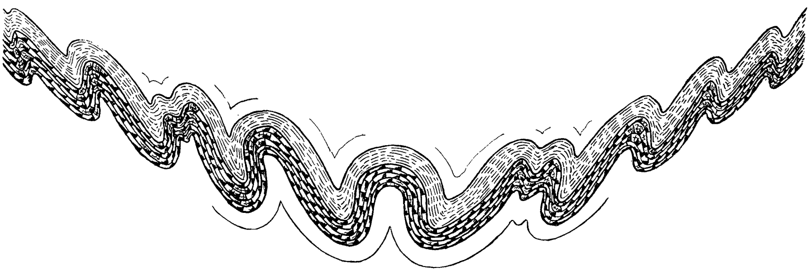

FIG. 14.—Ideal section of an upright abnormal synclinorium.

The upright abnormal synclinorium.—The primary fold of the upright abnormal synclinorium has a vertical, or nearly vertical, axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions. The primary fold is composed of a set of secondary folds, which at the trough are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial planes on opposite sides of the trough diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped (Fig. 14).

The inclined abnormal synclinorium.—The primary fold of the inclined abnormal syclinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, all of which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the trough diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The overturned abnormal synclinorium.—The primary fold of the overturned abnormal synclinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of secondary axial planes on opposite sides of the trough diverge upward and converge downward.

OCCURRENCE AND ORIGIN OF COMPOSITE FOLDS.

Higher orders of folds.—In all of the above cases the secondary folds of the primary anticlinoria and synclinoria may themselves be anticlinoria and syclinoria. The tertiary folds of the secondary anticlinoria and synclinoria may also be anticlinoria and synclinoria, and so on to the *n*th order. The higher orders of the anticlinoria and synclinoria are microscopic. Each higher order of anticlinorium and synclinorium may be described with reference to the anticlinorium and synclinorium of the next lower order in a manner similar to the description of the primary anticlinorium and synclinorium with reference to a simple fold of the first order of magnitude.

Even in regions of gentle folding, looked at in a large way, anticlinoria and synclinoria are the rule rather than the exception. In regions of moderately close folding the secondary anticlinoria and synclinoria, as a rule, are themselves anticlinoria and synclinoria. However, it is in such regions as the Alps, Canada, eastern United States, and Lake Superior that occur the complex anticlinoria and synclinoria composed of folds of different orders up to the *n*th order.

The primary anticlinoria and synclinoria are usually upright or slightly inclined. The higher orders of anticlinoria and synclinoria are usually inclined or overturned. The very large synclinoria and anticlinoria on the flanks of the massifs of the Alps, in the Green Mountains of Massachusetts, thc southern Appalachians, and many other mountain ranges, many of them miles in length, are to be considered as secondary folds composing a

part of the primary anticlinoria, each of which includes a central massif and both its flanks. By an examination of the published transverse sections of the Alps and Green Mountains (see Fig. 19) it will be seen that they are usually complicated fan-shaped anticlinoria, which are composed of complex normal and sometimes abnormal anticlinoria and synclinoria. In each normal anticlinorium, of whatever order, the axial planes of the folds of the next higher order diverge upward and converge downward, while in each normal synclinorium the axial plane of the folds of the next higher order converge upward and diverge downward. In the abnormal anticlinoria and synclinoria the reverse is the case.

Origin of normal folds.—As has been stated, the forces which act upon rocks when being folded are assumed to be tangential thrust and gravity. In the smaller folds, thrust may be thought to be the dominant force, the other being the modifying force of varying strength. In the great folds of the earth, gravity may be thought to be the dominant force, which by differential depression relatively raises a great anticline or depresses a great syncline, while thrust may play a subordinate part, being the dominant force in the production of folds of the second and higher orders. In folds of intermediate size, each of the forces may be about equally important. The relative value does not matter so far as the foregoing analysis is concerned, as in all three cases the resultant forms fall within the classes given. As long as we are so far from agreeing upon the forces which produce mountain ranges, and their manner of work, it seems best to classify the forms of folds as we find them, and to explain their origin so far as we are able. If thrust and gravity be conceived as acting uniformly upon horizontal homogeneous rocks, which are under such conditions as to bend without breaking, normal anticlinoria and synclinoria will be produced. Because of initial dips (as explained by Willis), or unequal superincumbent weight, or other causes, or one or more of these together, rocks when subjected to thrust and gravity rise into an anticline here or fall into a syncline there. But there is unequal weight upon

the different parts of each anticline and syncline. The large basins of deposition are not simple, but undulating. These secondary undulations are composed of smaller ones, and so on until ripple-marks are reached, and even these are composite. Each curve is composed of rhythmical curves of a higher order; hence the arch or trough which forms is not simple, but is composed of a number of minor folds, and these again of those of a higher order.

At first the anticlinorium is upright, or nearly so, as are also the folds of a higher order which compose it, but the secondary folds on the flanks of the primary fold point slightly outward, although the accommodations between the beds compensate in part for this (Figs. 15 and 16). As the limbs of the anticlinorium become steeper the secondary folds on the limbs are thrown farther and farther away from the axis of the primary arch (Fig. 7). If unaffected by other forces, when the primary fold becomes steep the secondary folds on the limbs become much inclined or overturned. When the limbs of the primary folds become vertical, the secondary folds on the limbs become lying or recumbent. In all cases, therefore, the axial planes of the secondary folds diverge upward and converge downward. The force of gravity may enter to further modify the forms of the folds. When a fold is inclined, its own weight and that of the superincumbent beds tend to push it over still farther. The effectiveness of gravity in this work is doubtless in part due in many cases to partial escape from thrust because of the relative rise above the deep-seated beds largely transmitting the horizontal force. (See p. 318). The farther the secondary folds are inclined, either by the increased steepness of the primary fold or by the effects of superincumbent weight, the more effective is gravity in pressing them down still farther (Fig. 8). When the weight of the superincumbent material is great, these folds may be pressed into a recumbent position, even where the primary anticlinorium is a gentle fold. Thus are explained the composite normal anticlinoria of the Alps.

At first a synclinorium is upright, or nearly so, as are also the

folds of the next order which compose it, but the secondary folds on the primary fold point slightly inward, although the accommodations between the beds compensate in part for this (Figs. 15 and 16; see p. 331). As the limbs of the synclinorium become steeper the secondary folds on the limbs are thrown farther and farther toward the axis of the primary trough. If unaffected by other forces, when the primary fold becomes steep the secondary folds on the limbs become much inclined or overturned. When the limbs of the primary fold become vertical, the secondary folds on the limbs become lying or recumbent. In all cases, therefore, the axial planes of the secondary folds converge upward and diverge downward. But the force of gravity enters to further modify the form of the folds. When a fold is inclined, its own weight and that of the superincumbent beds tend to push it over still farther. The effectiveness of gravity in this work is doubtless in part due in many cases to partial escape from thrust because of the relative rise above the deep-seated beds largely transmitting the horizontal force. (See p. 318.) The farther the secondary folds are inclined, either by the increased steepness of the primary fold or by the effects of superincumbent weight, the more effective is gravity in pressing them down still farther (Fig. 11). When the weight of the superincumbent material is great, these folds may be pressed into a recumbent position, even when the primary synclinorium is a gentle fold. In the synclinoria on the flanks of the Alps, which are secondary to the great primary anticlinorium, the crests of the recumbent secondary folds sometimes nearly meet, thus almost closing the synclinorium.

The question may be raised as to the effectiveness of superincumbent weight in pressing down inclined folds. It has been explained[1] that zones of folding of rock masses are necessarily zones of readjustment or of partial rock flowage. The flowage is from the places of great compression to the places of less compression. Where the weight of the superincumbent strata is so great as to equal or surpass the strength of the rocks folded, it appears

[1] This JOURNAL, Vol. IV., pp. 209–212.

clear that gravity must be an important force, which may greatly modify the forms of folds. The particular form of fold in a given case is of course the resultant of all the forces which work upon the rock stratum composing it.

So far as I am aware, Dana,[1] in 1847, was the first geologist to call attention to the principle that folds may be modified by the force of gravity. As is well known, this idea has been recently emphasized by Reyer.

Origin of abnormal folds. — In the abnormal anticlinorium and synclinorium new factors enter to modify the result. The first is readjustment between the beds. Fig. 15 represents a draw-

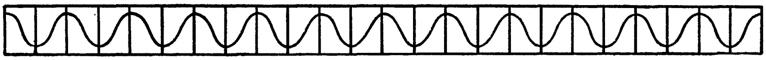

FIG. 15. — Representation of simple symmetrical folds, with their axial planes drawn on the ends of a bunch of smooth paper three-fourths of an inch thick.

ing of a number of upright folds made upon the ends of a bunch of smooth sheets of paper three-fourths of an inch thick. The sheets may be taken to represent thin beds in a nearly homogeneous rock. Fig. 16 represents this same drawing as it was distorted when the bunch of paper was folded into anticlines and synclines between blocks of wood. It will be seen that, consequent upon the readjustment of the sheets over one another, rendered necessary by the folding, the secondary folds at the crests and the troughs remain upright, although compressed if a secondary anticline or syncline corresponds with a primary fold of the same kind, and dilated if a secondary anticline or syncline corresponds with a fold of the opposite kind, and vice versa. If the secondary folds were slight, the opening might go so far as to obliterate them and the only remaining effect be to flatten the primary anticlines or synclines. The secondary folds on the limbs of the primary folds are distorted. The readjustment therefore mainly affected the forms of the fold upon the limbs. Taking as their axial planes the radial planes of the primary

[1] Geological results of the earth's contraction in consequence of cooling, by JAMES D. DANA, Am. Jour. Sci., 2d ser., Vol. III, p. 185, 1847.

folds, the secondary folds on the limbs are seen to be inclined. In reference to a primary anticline, the axial planes of opposite folds converge downward; in reference to a primary syncline, the axial planes of opposite folds diverge downward, but both less than they would were it not for readjustment. The above experiment does not exactly represent the conditions in nature, for the accommodations between the beds, instead of occurring parallel to the primary folds, would take place parallel to the secondary folds. However, an examination of the distortion of the axial planes of Fig. 15, shown in Fig. 16, shows beyond question that

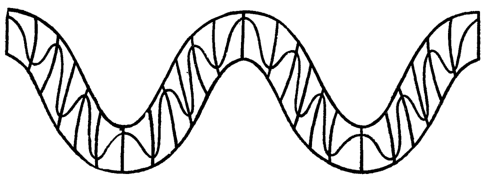

FIG. 16.—The same, as it was distorted when folded into anticlines and synclines.

when a set of beds is folded which are free to adjust themselves parallel to bedding, the movement of the material in the upper half of the beds is relatively away from a syncline toward an anticline, and the movement of the lower half is away from an anticline toward a syncline; or, stated more generally, the differential movement between any two adjacent beds on the legs of folds is relatively up in the higher bed and relatively down in the lower bed. It cannot be doubted that the sum total of the readjustments between the beds, although they follow the crenulations instead of being exactly parallel to the primary fold, would give the same effect. Therefore there is a tendency in anticlinoria and synclinoria, due to normal differential movement, for secondary folds to become inclined, taking the radial planes of the primary folds as axial planes of the secondary folds. However, when the readjustment is uniformly distributed this tendency does not so far affect the secondary folds but that they fall within the class of normal composite folds. But if the major readjustment of a great set of formations were largely concentrated along a

single one in it, anticlinoria might have the axial planes of the secondary folds converge upward and diverge downward, and synclinoria might have the axial planes of the secondary folds diverge upward and converge downward, and thus both become abnormal. This readjustment along the beds, as explained in my paper in the following number, may in many cases be considered as movements along shearing planes.

The second new factor in the production of abnormal folds is the great strength of the older rocks. For a given region, upon the average, rocks become stronger with increase of age. There are innumerable exceptions to this if too small portions of geological time be compared, as period with period, but comparing era with era such exceptions are rare or altogether absent. The Archean rocks are usually stronger than the Proterozoic, the Proterozoic rocks are stronger than the Palæozoic, the Palæozoic rocks are stronger than the Mesozoic, and the Mesozoic rocks are stronger than the Cenozoic. This in the sedimentary strata is due to the indurating effects of various geological forces. In mountain ranges, where complex anticlinoria and synclinoria mostly occur, a great thickness of strata is concerned in the major folds, in most cases more than the deposits of an era; so that upon the whole in great mountain masses the lower groups of rocks are stronger.

The third cause of the production of abnormal folds may be decreasing lateral stress with increasing depth. That such variation in stress is a general fact must be true if the theory of the level of no lateral stress at a moderate depth be correct. It has been pointed out (pages 210–212) that folds must die out with increasing depth unless there is great rearrangement of material. If it be supposed that the opposing stresses upon opposite sides of an anticline or syncline decrease with depth, there will certainly be more decided folding of the higher strata than of the lower. This implies upward differential movement of a higher stratum as compared with a lower beyond that required for normal readjustment. (See p. 331). Consequent upon this there will be a tendency for the axial planes of secondary folds on

anticlinoria to diverge downward, and for those on synclinoria to converge downward.

Another factor in the production of abnormal composite folds is the position of the fold in the group of rocks folded. The farther the rocks are below the surface the greater is the weight of superincumbent strata and the more forceful is gravity in pressing to a recumbent position the inclined secondary and tertiary folds of great anticlinoria or synclinoria. As has been seen, the inferior strength in the upper strata and the lessened weight to which the upper strata are subjected are not usually sufficient to prevent thrust and gravity from acting in the ordinary way and producing normal anticlinoria and synclinoria.

In both the abnormal anticlinorium and synclinorium the application of the above causes to their formation are identical. To make this clear the following figures are drawn: Figs. 17 and 18 each represent four strata, the lower two of which are strong and the upper two of which are weak, each figure comprising one-fourth of a wave and the other being its complement. In each case the figure ends on one side at the crest and on the other at the trough of the flexure. There is nothing to indicate whether either is a part of an anticline or a syncline. Each, in fact, may be half of either, for, put end to end in one way, they form an anticline; in the other, a syncline. In both cases the lower rocks constitute a relatively rigid inclined plane. If the superincumbent weight is not too great when thrust occurs, in certain cases the softer rocks above may yield to the forces to a greater degree than do the rigid rocks below, and thus tend to flow over them, and in case the upper strata be much weaker than the lower, or there be a plane of weakness, the differential flow will be largely concentrated along the contact or weak zone, and normal secondary folds which have before developed may be inclined in an opposite direction from their first position, so as to become abnormal. This case is represented by the middle parts of Figs. 17 and 18. Put together end to end in one way the prominent secondary folds form an abnormal anticlinorium; in the other, an abnormal synclinorium. It will be noted that

in passing away from the central zone of plications either into the more rigid rocks below or into the softer rocks above the secondary folds become normal. Considering the two figures put together to represent a great flexed mountain mass, and supposing erosion to truncate the layers to the horizontal line drawn, there would be exposed normal folds at the center of the anticline, abnormal ones upon the flanks, and normal ones at the outer parts of the mountain mass. In nature we can never hope to see such a great composite fold in all its parts. It is only in the great mountain masses where such folds have been dissected that we can get at their character. In such cases the older and newer strata would be expected to show the normal forms, the intermediate strata the abnormal forms. The change from normal to abnormal and to normal again is apparently that which actually occurs in the Alps from the St. Gothard massif south to the great valley of Switzerland.

The manner in which the more rigid rocks escape large plications while the weaker beds are strongly plicated, producing abnormal folds, is well shown by Fig. 13, given by Heim as a general section showing roof structure in folded sediments and a central massif. In the production of actual abnormal anticlinoria and synclinoria it is probable that accommodations as illustrated by Figs. 15 and 16 are largely concentrated as illustrated by Figs. 17 and 18. Therefore the production of abnormal anticlinoria and synclinoria may be summarized as follows:

When two groups of rocks of unequal strength, not deeply buried, are folded into an anticline, on account of the natural readjustment of strata, of the relative weakness of the upper, newer group of rocks, and probably of decreasing differential stress with increasing depth, there may be differential flow on either side toward the axis of anticlinorium over the lower, older rocks, thus producing secondary folds, the axial planes of which converge upward and diverge downward. Had the rocks been of equal strength, or had the weight of the superincumbent strata been sufficient to more than overbalance the difference in strength and difference in stress tending to produce folds point-

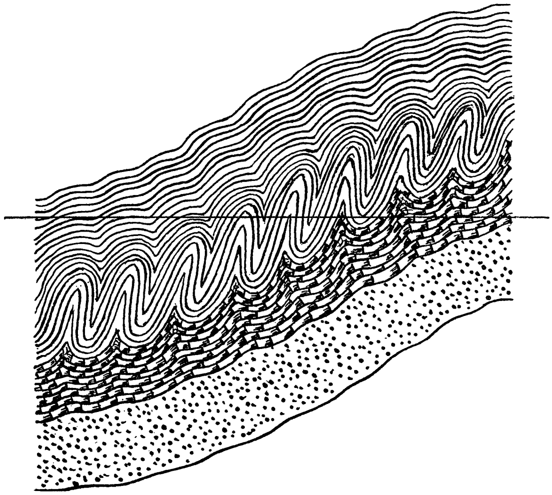

FIG. 17.

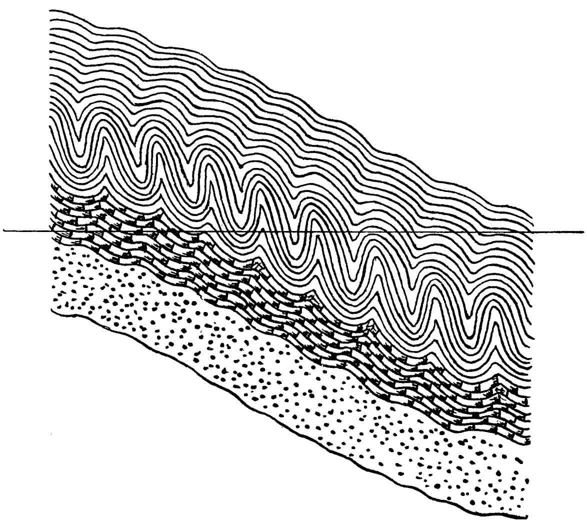

FIG. 18.

FIGS. 17 and 18.—Observe halves of composite folds, showing development of abnormal folds and their relations to normal folds.

ing crestward, normal secondary folds pointing outward would have developed.

When two groups of rocks of unequal strength, not deeply buried, are folded into a syncline, on account of the natural readjustment of the strata, of the relative weakness of the upper, newer group of rocks, and probably of decreasing differential stress with increasing depth, there may be differential flow of the rock material on either side away from the axis of the synclinorium over the lower, older rocks, thus producing secondary folds, the axial planes of which diverge upward and converge downward. Had the rocks been of equal strength, or had the weight of the superincumbent strata been sufficient to more than overbalance the difference in strength and difference in stress tending to produce folds pointing troughward, normal secondary folds pointing inward would have been developed.

Crystalline or core rocks are apt to be more massive and stronger than the little altered sedimentary beds, and therefore the core rocks usually act to a certain degree as a unit when subjected to thrust. Secondary abnormal folds are frequently found at the contact of massifs and the overlying rocks. However, even in these cases the folds will be normal if only the thickness of the superincumbent beds be sufficient. At a considerable depth the different strength of rocks is not so potent as gravity in giving form to folds. From the above it does not follow that the massifs or portions of them do not take part in the folding. That they do in many regions is certain, as is shown by infolding of core rocks with sedimentary beds, even when the massifs were originally granite. Also that massifs may take part in the folding is shown by the minor and major folds of their parts, which in form are like those of the associated sedimentary rocks.

It is recognized, however, as explained upon a subsequent page, that massifs, because of their homogeneous character, because they are underlain by no definite stratum of rock of a different character, and because they are often so deeply buried, may act in quite a different fashion, under the forces of folding, from ordinary sedimentary layers.

Causes modifying the forms of folds.—The foregoing discussion has been carried on as though the active forces of deformation are equal in opposite directions, and are acting in the same zone from opposite sides of the deformed area. If this were the case if the strata affected were of the same thickness and strength, if the initial dips were equal in opposite directions, and if the other conditions were the same, a strictly symmetrical arrangement of folds might be expected. But these conditions are never true. In the great majority of cases the facts do not depart so far from them but that the folds which form fall within some of the classes given. However, there are a number of ways in which the forms of folds may be modified.

Major faulting may interfere with their forms. Minor slip-faulting, as explained upon a subsequent page, may dominate an entire area. Igneous intrusions may disturb beds in many ways. Where these modifying causes are found the structure is the resultant of all the movements.

Finally it often happens that there is a tendency for the axial planes upon one side of an anticlinorium or synclinorium to be steeper than those upon the other. In some cases the axial planes of all the folds throughout a mountain mass may be inclined in the same direction. Such folds may be called *monoclinal.* In such cases the force, and consequently the movement of the strata, have usually been supposed to be more largely from one direction than from the other, and the axial planes of the folds have usually been regarded as dipping toward the force.

Various explanations have been offered as to how the forces act upon the strata in the actual production of monoclinal folds. Of these explanations, that offered by Rogers appears most probable for piles of strata of like rigidity. Believing as he did that the folds of the Appalachians were analogous to the waves of the sea, he naturally concluded that the tendency to a southeastward inclination of the folds of the Appalachians was due to the fact that the center of disturbance and resultant waves came from the southeast. While not following him in his explanation of folds as great waves suddenly formed, the idea seems reason-

able that the "forward thrust operating upon the flexures . . . would steepen the advanced side . . . precisely as the wind acting upon the billows of the ocean forces forward their crests and imparts a steeper slope to their leeward sides." [1] For we now regard folded rocks as plastic when bent. The compressive stresses do not extend to an indefinite depth, but are limited by the level of no lateral stress. They therefore affect the outer skin of the earth, just as does the wind the superficial water of the ocean. As a result there is a differential movement due to friction, the amount of movement upon the average gradually decreasing below the zone of maximum movement. Of course the sums of the forces, including friction are always equal in opposite directions, but they constitute a vertical couple, *i. e.*, "Two equal and parallel forces opposed in direction, but not in the same straight line." As a result there is differential movement of the material of the upper zone as compared with the lower, the former being thrust over the latter.

Other things being equal, where the differential thrust is greatest the first inclined fold is formed. The folding piles up the strata. After a time the increased thickness of material is sufficient to present a larger total resistance to deformation than the thinner strata in advance. This stress will then be transmitted forward. On account of the greater stress per unit of area, a second fold, similar to the first, will then be formed, but this results in again thickening the mass subject to the force couple, and again the stress is transmitted forward. A new inclined fold is then produced, and so on.

It is not necessary that one inclined fold shall be completely formed before others begin to develop. Indeed, this is not to be expected, for as soon as any thickening of the deformed mass occurs the conditions are favorable for the forward transmission of the effective stress. Thus many folds may be in process of formation at the same time and so far as I can understand,

[1] On the Physical Structure of the Appalachian Chain, as exemplifying the laws which have regulated the elevation of great mountain chains generally, by W. B. ROGERT, Proc. Assn. Am. Geol. and Nat. for 1840–2, p. 512, Boston, 1843.

there is no reason why differential movement should not be initiated at the same time wherever the conditions are favorable throughout the area in which monoclinal folds are observed.

It is to be noted that, under the assumption that the effective stress moves the upper strata over the lower, the vertical component of deformation is upward rather than downward. In other words, it is in the direction of easiest relief, and this is the kind of deformation one would expect, and which doubtless prevails in the majority of movements of the first order, in which thrust is the dominant force, for it has been seen (p. 332) that, upon the average, rocks are stronger with increasing age, and hence, there is greater resistance centerward than surfaceward, Folds thus produced by upper differential movement may be called "overthrust folds." The axial planes dip toward the effective stress, hence *overthrust folds are those in which the axial planes dip toward the force producing them.*

While the development of overthrust folds is the general law, it may not infrequently happen that under favorable conditions beds or formations may be thrust forward and downward. Folds thus produced by downward differential movement may be called "underthrust folds." The axial planes dip away from the effective stress, hence, *underthrust folds are those in which the axial planes dip away from the force producing them.*

In the rocks of a system or group strong formations may be above weak formations. In this case the strong formations are able to transmit the forces to a greater degree than the beds above or below. As pointed out by Willis, a forward downward movement may be directed by initial dip, and thus underthrust folds be produced. In a second case the strata pile up as a result of the folding. The relatively raised masses may then to a certain extent escape active thrust. (See Fig. 6 and p. 318.) The strata largely transmitting the thrust in front of the folded material may under these conditions be pushed under the higher mass. Underthrust folds are most likely to occur if the two conditions above given favorable to their formation are combined, *i. e.*, weak formations below and piling up of strata.

In considering the force couples in normal and abnormal composite folds, each composite limb between trough and crest must be separately analyzed. (See Figs. 17 and 18.) In normal anticlinoria and synclinoria gravity has been seen to be the efficient force which causes differential movement (pp. 328–330). Gravity works down the slope. The axial planes of the secondary folds dip toward the force (see Figs. 8 and 11), and the secondary crenulations are therefore overthrust folds. In abnormal composite folds it has been explained (pp. 330–333) that the differential movement may be caused by (1) normal readjustment, (2) increased strength of the rocks with increasing depth, and (3) the possible decreasing lateral stress with increasing depth. The first of these is eliminated for the present purpose. The second and third, either singly or together, must be sufficient to overcome gravity and to give a resultant force directed up the slope, in order that abnormal folds may be formed. (See Figs. 12 and 14.) The axial planes therefore dip toward the force, just as in normal composite folds, and the secondary crenulations are therefore overthrust folds.

By the above it is not meant to imply that underthrust folds may not be produced in either normal or abnormal composite folds, for if the conditions given on previous pages favorable for underthrust folds locally occur, crenulations of this type may be formed.

The formation of monoclinical folds is sometimes well illustrated by the crenulations of a lava bed in which there was differential flow down a slope, the upper layers moving faster than the lower. Monoclinal folds thus formed are usually not large. The directing force was gravity, and the axial planes dip toward the force. The crenulations are therefore overthrust folds. Since ordinary folds, which form without fracture, develop in the deep seated zone of flowage, the analogy with contorted lava currents is believed to be closer than might be at first thought, although it is not meant to imply by this that the folded rocks are really fluid, but merely that a plastic solid under sufficient differential stress is deformed in the same fashion as is a viscous liquid.

It has been pointed out (p. 331) that in ordinary folds the movement is relatively up for a higher stratum as compared with the one next below it. In the case of overturned monoclinal folds (Figs. 3 and 4) the later differential movements of the strata on the longer limbs of the folds may continue quite to and past the crests of the anticline, so that the differential movement on the shorter limbs of the folds is relatively down for the superior stratum geologically as compared with the inferior. However, in this case, when the folds are overturned, with reference to the horizon on the inverted limb, the movement of the higher stratum would still be upward, as compared with the one below it. This may be called *reverse differential movement*, and it may continue so as to more than compensate for the normal differential movement, but the resultant differential movement would be less on the steeply inclined or overturned limbs of the folds than on the longer, flatter limbs, since on the latter the motion is continuously in the same direction.

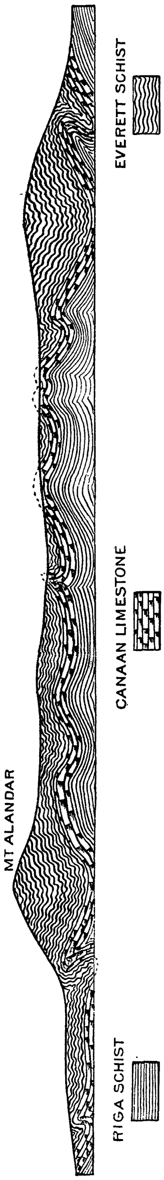

FIG. 19.

In the case of monoclinal folds it will be shown in my paper in the following number of this JOURNAL that the shearing is greater on the longer, more gently inclined limbs than on the shorter, more steeply inclined limbs. As a result of this the former are not so thick as the latter and are usually more metamorphosed.

Examples of composite folds.—In the United States, Mount Greylock, the Taconic range, and the valley between constitute a great normal anticlinorium. The same is true of Mount Washington, in Massachusetts (Fig. 19). A cross-section of the central part of the Marquette district furnishes an example of a great abnormal

synclinorium. The abnormal character is due to the very great difference in strength between the Archean granite and the Algonkian Lower Marquette formations. At the east end of the Marquette district, where the Archean rocks are relatively weak schists, the synclinorium is normal.

Limit of term fold.—By the above analysis and examples it is not meant to imply that, where sediments were deposited off a land area and the land and sea areas were afterwards compressed, producing undulations in the sedimentary rocks, and often in those also of the original land areas, the terms anticlinorium and synclinorium are properly applicable to the primary flexures. Following Dana, as indicated on a previous page, such flexures are more properly described as geanticlinès and geosynclines. In such cases, however, there is a differential uprising or subsidence, in many cases producing a composite flexure. It is believed that the principles applied to primary folds of true anticlinoria and synclinoria apply to the secondary folds in question. just as though they together constituted a part of an ordinary fold. When gravity controls their form they are normal. When the difference of strength of the rocks controls their form they are abnormal.

As a matter of fact, it is often difficult to determine in a given mountain range whether the so-called core rocks were deeply buried under a great thickness of sediments, being, perhaps, in or near the center of the trough of deposition, or whether they were, and continued to be, land areas. It is thought that it is one of the advantages of the treatment given that it is not necessary to decide this question before working out the structure of the district. In either case the types of flexures of the second and higher orders formed on the primary flexures and the laws controlling them are the same.

Movements continuous or discontinuous.—Composite folds may be the result of forces acting continuously or discontinuously. The different secondary folds may develop at different times. The higher orders of folds may begin to form only at a late stage of development. Usually it is impossible to determine whether

thrust was continuous or discontinuous. However, if the intervals between the successive movements were sufficiently long and the conditions were such that crevices could be formed and these were filled with secondary minerals, or if cementation or metasomatic changes produced new minerals, or if within the strata igneous rocks were intruded, the later dynamic effects upon such new material may enable us to determine the fact of different movements.

In the Hiwassee section of the Ocoee series, in the southern Appalachians, in the more closely folded part of the section, quartz veins have formed in a first set of crevices. The rocks have been subsequently folded so as to closely plicate these veins, and after this folding a second set of unfolded quartz veins has formed. In other parts of the section only unfolded quartz veins are seen. This shows that certain parts of the area were affected by two periods of folding separated by a long interval.

COMPLEX FOLDS.

ORIGIN OF COMPLEX FOLDS.

Thus far folds have been considered in two dimensions only and have been treated as though they were continuous and had continuous axial lines, each one being a great circle of the earth. Such is not the case in nature. In a given fold, in passing from place to place, the direction and inclination of the crest-line are different, and it is rarely, if ever, a part of a great circle. Its deviation from the horizontal at any point gives the inclination of the fold at that point. This inclination, measured in degrees, is known as the pitch. Also when a fold is followed longitudinally, or in the third dimension, it changes continuously in size and character. A fold of the greatest magnitude may be followed along the third dimension until it dies out. The most closely compressed and intricately composite fold may be followed in the third dimension until it becomes a gentle composite fold or even disappears. When a primary fold is traced in the third dimension it may be found to grade into a secondary fold. At the same time a secondary fold on the flank of a primary fold

may itself become the primary fold. On any fold a new secondary fold may appear, and when followed longitudinally may become more and more important until it is the dominant fold. In short, in a composite set of folds each fold of any order is constantly changing in character and importance.

In a given fold all of the changes may occur, and thrust may have acted only in a single direction. The initial dip of the beds may have been different. The thickness and strength of the beds may have varied from place to place. Thrust may not have been equal along the border of the entire area affected. It may not have continued to act as long in one place as in another. Therefore there is great variation in the character and size of folds at their different cross-sections. Gravity is always toward the center of the earth; therefore variation in its direction does not enter as a modifying force.

Further, in the foldings of rocks thrust is rarely, if ever, in a single direction. Usually, when complex thrusts are decomposed in two directions at right angles to each other, one is more powerful than the other. The greater force may be called the major thrust, and the lesser force may be called the minor thrust.

Major and minor thrusts may unite in a resultant effect and produce a set of folds in a position intermediate between those that the two sets would have if each thrust had been alone. It is possible and even probable in many cases, that after a thrust in one direction has produced a set of folds, a new thrust at an angle less than a right angle to the first may be decomposed into two forces and result in further folding the first set of folds, and perhaps in the production of transverse folds, rather than in producing a new diagonal set; for when rocks are once bent in a given place they bend farther much easier at this place in the same direction than at a new place in a new direction. This principle is well illustrated by the folds of the Jurassic limestone of the Jura Mountains (Fig. 6). The transverse component of the lateral thrust may be too weak to produce any considerable effect. In such cases it would be difficult or impossible to discriminate a set of folds thus formed by two diverse thrusts from a set

formed by simultaneous or successive thrusts in a uniform direction. However, if there be sufficiently strong thrusts in two or more diagonal directions, or two thrusts at right angles, two sets of folds are produced which intersect each other. Such a district may be described as one of complex folding. The more important set of folds, corresponding to the major thrust, may be called the major or longitudinal folds, and the cross folds, corresponding to the minor thrust may be called the minor or transverse folds.

CHARACTER OF COMPLEX FOLDS.

From analysis, as well as from observation, it is found that cross folds are usually nearly at right angles to each other ; for as already explained, if the diverse thrusts be inclined to one another, they will be resolved into two forces, one of which forms the major folds, and the other of which produces cross folds in a direction at right angles, or nearly so, to the first set of folds.

Major and minor cross folds may be produced by continuous forces in both directions, or in each direction each force may be continuous or discontinuous. To ascertain these points the same criteria are available as in the case of thrust in a single direction (see pp. 342–343).

Longitudinal and transverse folds may each be classified into upright, inclined, or overturned. Each of these may be ordinary, isoclinal, or fan-shaped. Simple folds may unite to form composite folds. The composite folds may be normal or abnormal, and each synclinorium or anticlinorium under each class may be upright, inclined, or overturned.

As complex folds actually occur in the field, usually the compression is not close in both directions. Cases are known, however in which a set of longitudinal overturned folds have transverse folds with vertical dips, and the dips of the transverse folds in intricately folded districts are in many cases as steep as 45° or 60°.

When the major folds are close, as compared with the minor folds, the complex folds have great length as compared with the breadth and are canoe-shaped. The Appalachians in the closely

folded districts may be taken as a type of such complex folding. That initial dip is not sufficient to explain the pitch of the folds in this region is shown by the following facts: A stratum or set of strata may rise at one end of a synclinal canoe. Beyond this for a distance the strata are removed by erosion, but farther on appear again plunging downward at the end of another canoe. Corresponding phenomena are observed in reference to anticlines.

In proportion as the major and minor thrusts approach each other in power, the canoes become shorter and broader. Where they are nearly equal the folds are domes and basins. Usually these domes and basins are associated with canoes, which may be in one or two directions in the same region. Where the two sets of cross folds are about equally conspicuous the strikes and dips of the rocks vary constantly, their directions depending upon what part of the complex folds is under observation.

Where the complex folds are also composite the canoes, domes, and basins are fluted or crenulated, being composed of secondary canoes, domes, and basins. Similarly, these may be composed of canoes, domes, and basins of the third order, and so on.

OBSERVATIONS IN COMPLEXLY FOLDED DISTRICTS.

From the relations of cross folds, as above explained, it is clear that where there are complex folds the axes of one set of folds and their pitch give the direction and dip of the cross fold at that point. Therefore to fully understand a district complexly folded it is necessary to make the following observations:

(1) Determine the strike and dip of the strata at a given point. These give the resultant position of the strata as tilted by the forces of folding in both directions.

(2) Determine the direction and pitch of the axes of the major folds. The first is the direction of dip and the second is the amount of the dip of the minor or cross folds. The average strike is, therefore, determined.

(3) Determine the direction and pitch of the axes of the minor folds. The first is the direction of dip and the second the

amount of the dip of the major folds. The average strike is, therefore, also determined.

Of these three observations, the first is the only one ordinarily taken, and it is the one of the least importance in regions of close, complex folding. It is only by making the second and third observations that an adequate idea of the structure can be obtained. While the first observation may be made at any point, the second and third observations can be made accurately only along the crests of the anticlines or troughs of the synclines of the various orders of folds. Therefore, it may be necessary tc work over a considerable area in order to obtain the required data. Some practical suggestions may be offered as to the manner of determining whether or not the rocks of a district are complexly folded, and if so folded, the direction and pitch of the axes of each set of folds, and therefore the strikes and dips of the two sets of cross folds.

(1) It is advisable to look for the ends of canoes. These may be frequently found at the ends of ridges; hence especial study should be made of the folds where a topographic break appears across the ordinary ridges, either at a right or an acute angle. When once the end of a canoe is found, an observation can be made as to the direction and pitch of the axes of the fold, and thus the strike and dip of the cross fold be determined.

(2) The tops of ridges should be examined. These may be the crests of anticlines or the troughs of synclines, depending upon the topographic development of the region. Along the little cross breaks which are sure to occur, the direction and pitch of the axes of the folds may be determined. In some instances ridges are longitudinally inclined, following hard layers, and in this case there is an exceptionally fine opportunity to determine the direction and pitch of the folds.

(3) In case the two sets of cross folds are about equally conspicuous, there may be a double set of ridges and valleys cutting each other at right angles, or nearly so, and this may give a clue to the character of the folding of the district.

(4) In some cases the beds are closely plicated in one direc-

tion so as to give nearly uniform strikes. Unless closely observed it may not be noted that there are really minor rapid deviations of strike, which indicate a set of pitching folds, and a complexly folded district. The major and more important folds may be transverse to the minor plications. From what has gone before, it is plain that in such cases the important observations are not the strikes and dips of the strata of the minor folds, which vary momentarily, but the direction and pitch of the axes of the minor folds, which give the direction and amount of the dip of the major fold, and therefore the average strike.

(5) Pumpelly has called attention to the fact that discordance between strike of bedding and that of secondary structures indicates pitching folds. Where a secondary structure develops at right angles to the greatest normal pressure, or nearly so, it in many instances has a nearly uniform direction for an extensive area. In case the folds are horizontal, or the district is simply folded, this direction is the same as the strike of the rocks or the strike of the axes of the folds. Where the forces producing the folds are in two or more directions, and consequently form complex folds, the minor component, producing pitch, does not develop cleavage at right angles to itself; and the relations between the strike of bedding and that of the secondary structure vary from near parallelism on the limbs of the longitudinal folds to a direction at right angles to each other at the ends of the canoes and on the crests of the anticlines and in the troughs of the synclines. In passing from one place to the other there are found all relations between parallelism and perpendicularity. Because the area where the two are parallel, or approximately so, is greater than the area where there is an important discordance between the two, it has been customary for text-books to speak of the strike of bedding and the strike of cleavage as usually parallel. This, as has been seen, is wholly true only where the folds are horizontal, and the statement becomes more and more a partial truth as the pitch of the folds increases in amount—that is, as the less conspicuous folds become more important. Hence it is that where a secondary structure exists the relations which

obtain between its strike and that of bedding should be ascertained, and if discrepancies are found this indicates a complexly folded district.

(6) Pumpelly also formulated the principle that "The degree and direction of the pitch of a fold are indicated by those of the axes of the minor plications on its sides." This statement must be understood to apply to the direction and pitch of the primary fold at the point where the secondary fold is observed. This principle is a direct corollary from the relations of cross folds as given on a previous page, and it is of the greatest service in determining the structures of very complexly folded districts, because in them minor plications are so numerous. They may be seen in their entirety, and may therefore give the required determination of the character of the cross folds. The principle is, however, only approximately true. It would be wholly true if the secondary folds upon the flanks of the primary fold were exactly of the same character as the latter. But since the forces locally vary in direction and amount, and the rocks vary in rigidity, the direction and pitch of a secondary fold may vary somewhat from those of a primary fold. Usually this deviation is so small that the principle is invaluable in field work in regions of complex folding, and gives data of sufficient accuracy for ordinary purposes.

It is evident that in the application of all the above criteria we must consider bedding and not secondary structure. The criteria upon which this discrimination is made will be considered in a later paper.

Very often in regions of complex folding observers note only the most conspicuous folds in a single direction. The fact that folds are composite may be overlooked, and that they are complex is even less likely to be seen. The difficulty is further increased because of faults and secondary structures, such as slatiness, schistosity, and banding, which may be mistaken for bedding. The development of these structures and their relations to folds and bedding will be considered in following papers.

In ordinary districts where there are cross folds the more

conspicuous set is generally chosen as giving the direction of folds, while the less conspicuous set in the other direction is considered as giving the pitch of the folds. It does not follow that the folds giving the pitch, in the magnitudes of their vertical components, are less important than the more conspicuous longitudinal folds, for the lowness of the dips of the transverse folds may be more than compensated by their greater lengths, and the cross folds may be of the first order of magnitude in a district. Usually it is possible to work out the structure of such a district without particular attention being directed to transverse folds. They are so gentle that the changes of strike and dip are not rapid, and a satisfactory map may be made without recognition of the existence of cross folds. It is suspected that the largest folds of a district have often escaped the attention of the geologists who did the mapping.

The more complex the folding of a district the more necessary it is in determining its structure to consider the character of both sets of folds, and for very complex districts this is imperative.

By means of maps and sections it is difficult to represent the structure of a very complexly folded district, and even a dissected model does not represent it completely, as it is impossible to show in true porportion the different orders of folds, and especially those of the higher orders. It is plain that cross-sections in a single direction at long intervals fail to give any adequate idea of the structure of such a district, although these combined with geologic and topographic maps may do so. In reports the structure can best be represented by combining the geologic and topographic maps with two sets of cross-sections made at frequent intervals and at right angles to each set of folds.

It will be noted that in the foregoing treatment of folds they are classified as they occur, no ultimate theory of their origin being offered. No conception of the causes of mountain ranges enters into the analysis. It is true that an explanation is attempted of the difference between normal and abnormal composite folds. The fact that this explanation apparently accords

with the forms and distribution of folds in all of the many different districts to which it has been applied, and at the same time accords with the principles of mechanics, appears to me to give to it a considerable degree of probability. Even if the explanation be not accepted, the forms of folds and the principles applicable to their study remain the same. Thus we have a classification of folds and an outline of methods for their study which will assist in determining the structure of the complexly folded districts and in preparing areal maps of them.

CHANGES ACCOMPANYING FOLDING.

Contemporaneous with rock folding, and in a large measure dependent upon it, other changes occur in rocks. As has been seen, crevicing and brecciation largely depend upon the same forces as does folding. During the process of folding old minerals are transformed into new ones. New mineral material enters from the outside. The minerals are rearranged and mechanically modified. Secondary structures, such as cleavage fissility, joints, and faults may develop. In short, during the folding process the rocks are to a greater or less degree metamorphosed.

RELATIONS OF FOLDS AND UNCONFORMITY.

The folding of a set of inferior formations in a more compli cated manner than that of another set of superior formations may indicate a structural break between the two, and consequently that the two sets of formations belong to different series. In order that this criterion may be applied, it must be conclusively shown that the supposed upper formations are really above the others. It must not be assumed that a formation at one side of an axis of plication is in a superior position because less folded, for in many regions close folds die out within a comparatively short distance in a direction transverse to them. This is the case along the Green Mountains, where the closely folded Lower Palæozoic rocks pass quickly, to the westward, to unfolded or very gently folded ones. The change here takes place so rapidly that it has been supposed by many geologists that the more closely

folded rocks are really the older and belong to a series prior to their unfolded westward continuation. The failure to appreciate the above principle has been to a large degree the cause of the Taconic controversy.

It is believed that the cause of the frequent sudden change from closely folded to very gently folded rocks across the strike of the folds is due to the principle explained on pages 317–318. This is: Strata when once bent at a certain place continue to bend at this place rather than to form a new fold. This bending continues until, as a result of the folding, the strata are greatly thickened and the inclinations become steep, so that resistance to further folding at this place is greatly increased. The force is then transmitted forward and a new area is affected by folding, but as soon as the strata are here bent they continue to bend easily until they are closely folded, so that there is the same sudden transition as before from the closely folded to the very gently folded or unfolded districts.

In the first and simplest case the lower formations have been subjected to either simple or complex folding, while the upper formations are undisturbed or very slightly disturbed. In this case the upper formations are likely to be found as inlyers upon the other, and the structural break between the two is comparatively easy to determine. Phenomena of this kind are found at many localities between the Palæozoic and pre-Palæozoic sediments, and less frequently they are found wholly within the pre-Palæozoic formations.

The second case is that in which the lower formations were folded by one or more movements before the upper series was deposited, and subsequently the two were again folded. If the second folding was of a comparatively simple character, and the earlier was rather complex, it is usually comparatively easy to separate the two series. For instance, the lower formations may have been rather closely folded by the first orogenic movement, and the two sets of formations together may have been gently folded by the second movement. The discrepancy between the two may often be detected, even when the movements were in

the same direction, as they so frequently were. But the discordance may be more easily discovered if the second movement was in a different direction from the first, so that the first folds of the lower formations become complexly folded at the second period of folding, the newer formations at the same time being simply folded.

Third, in more complicated cases the lower formations were folded one or more times before the upper series was deposited, and after the deposition of the latter the two series were again folded in a complex fashion, either by a single orogenic movement or else by successive movements. In proportion as the folding of the later formations becomes complicated the criterion of folding for separating series is more and more difficult to apply, and where the folding of the upper formations is at all intricate it is usually of little value. The criterion of folding for separating uncomformable series is to be considered in all cases in connection with other criteria.

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